$\Upsilon(5S)$ Physics at Belle:
opening up a new frontier

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Fermilab Joint Experiment/Theory Seminar
August 27th, 2010

- *data sets*
- *Cabibbo-favored B_s decays*
- *B_s decays to CP eigenstates*
- *B_s charmless decays*
- *radiative B_s decays*
- *$\Upsilon(5S) \to \Upsilon(nS)\ \pi\pi/KK$ decays*
- *$\Upsilon(5S) \to BB(\pi)$ decays*
- *Future*

Why study B_s decays at the $\Upsilon(5S)$?

- *Many final states can be reconstructed that are difficult/impossible to reconstruct at a hadron machine, e.g., $B_s \to \phi\,\gamma,\ \gamma\gamma$*

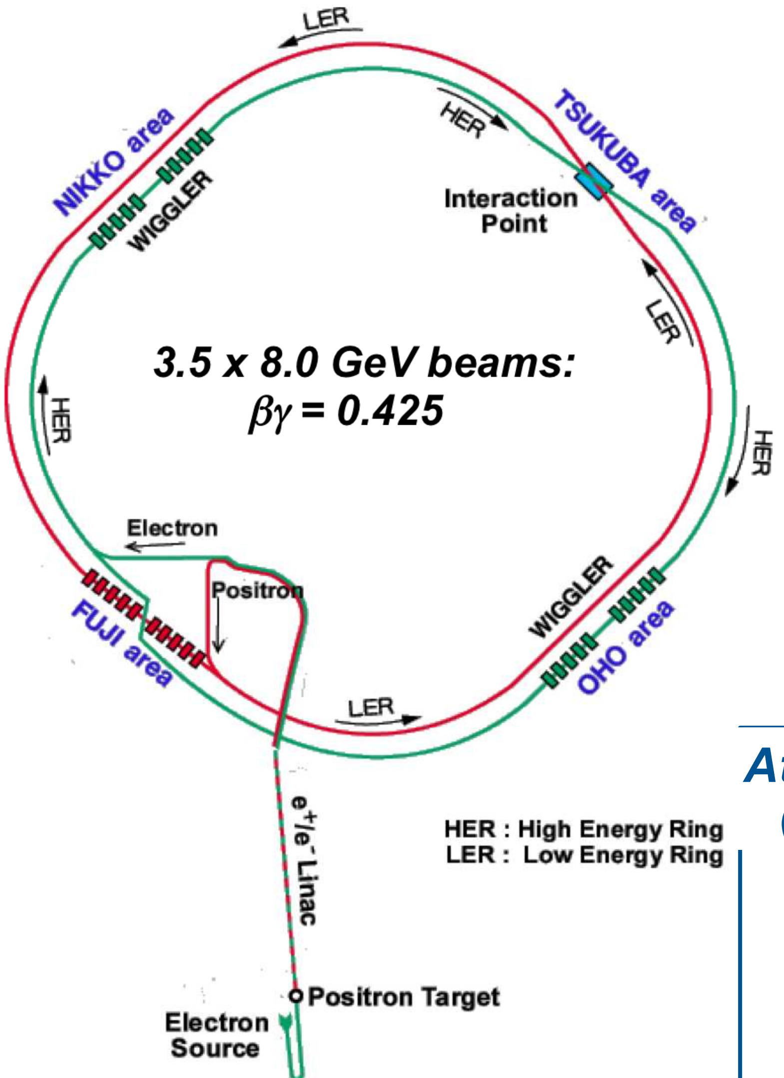
- *Due to low backgrounds and high efficiencies, one can reconstruct very high multiplicity final states, e.g., $B_s \to K^+K^-\pi^+K^+K^-\pi^-$*

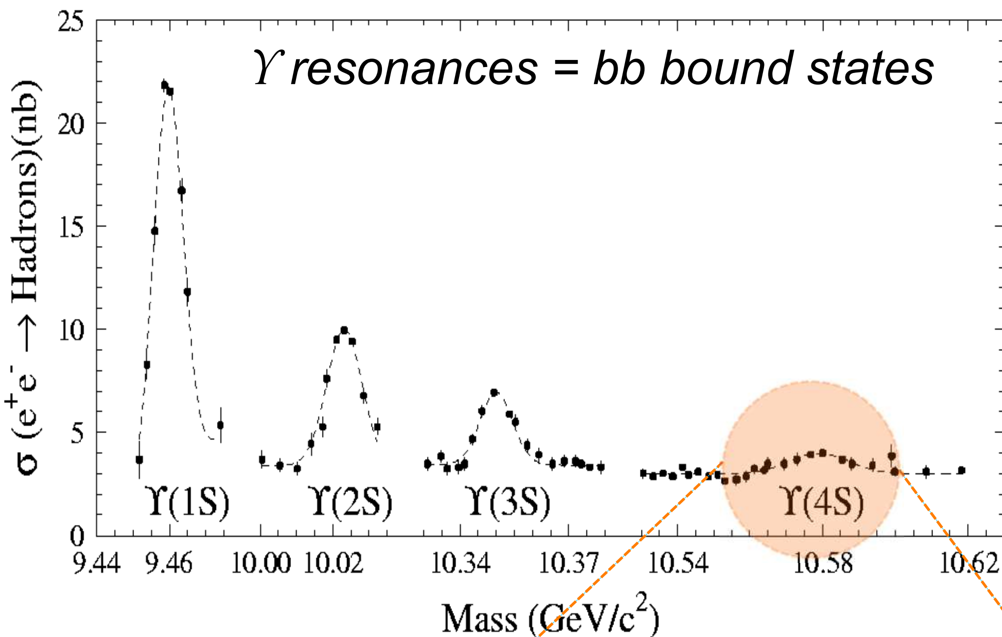
- *One can fully reconstruct one B_s, then look for the other B_s in the event $\Rightarrow$ measure absolute branching fractions*

- *Many backgrounds can be measured/calibrated using data from the $\Upsilon(4S)$, from the continuum, and from various control samples*

KEKB: most running at the Υ(4S) resonance:

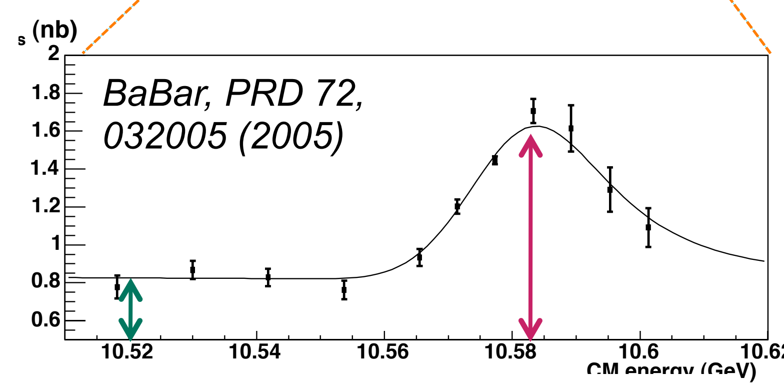
KEKB collider:





At Υ(4S) resonance:
($\sqrt{s}$ = 10.579 GeV)

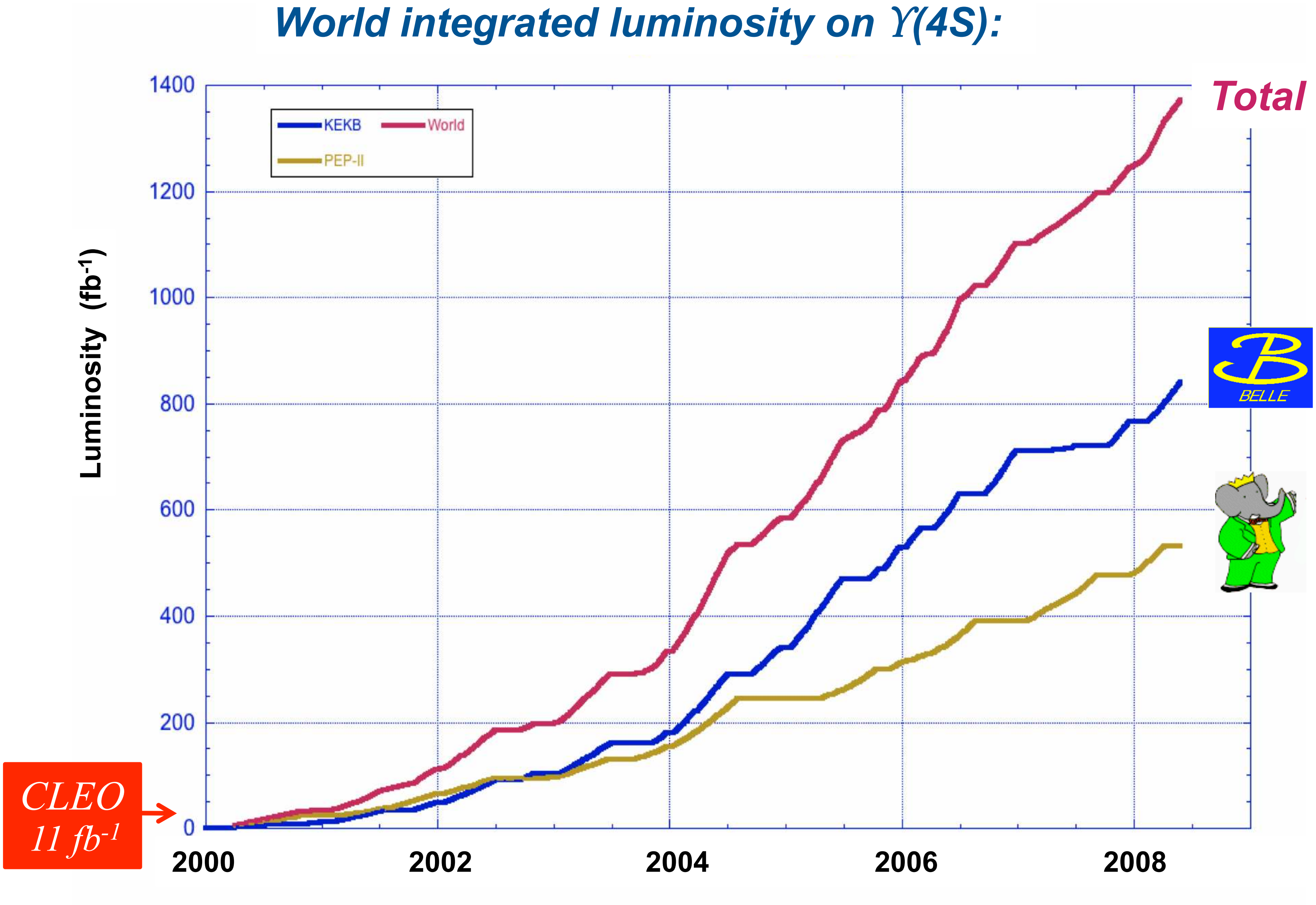
$\sigma(bb) \approx 1.1$ nb
$\sigma(cc) \approx 1.3$ nb
$\sigma(uu) \approx 1.4$ nb
$\sigma(dd,ss) \approx 0.3$ nb



off-resonance | on-resonance

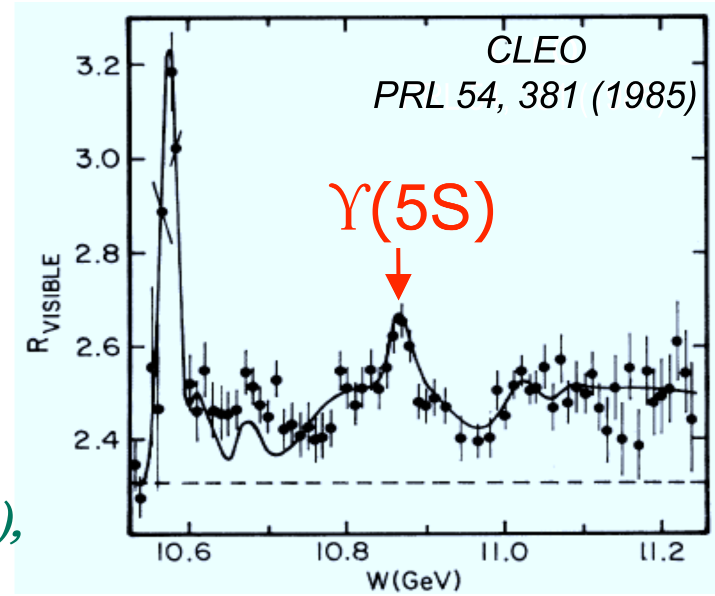
B factory performance:

World integrated luminosity on $\Upsilon(4S)$:



$\Upsilon(5S)$ production; how many B_s decays?

$e^+e^- \rightarrow \Upsilon(5S) \rightarrow B^0 B^0,\ B^{0*} B^0,\ B^0 B^{0*}, B^{0*} B^{0*},$
$B^+ B^-,\ B^{+*} B^-,\ B^+ B^{-*},\ B^{+*} B^{-*},$
$B^0 B^0 \pi,\ B^{0*} B^0 \pi,\ B^0 B^{0*} \pi, B^{0*} B^{0*} \pi,$
$B^+ B^- \pi,\ B^{+*} B^- \pi,\ B^+ B^{-*} \pi,\ B^{+*} B^{-*} \pi,$
$B^0 B^0 \pi\pi,\ B^+ B^- \pi\pi,$
(19 ± 3)% → $B_s B_s,\ B_s^* B_s,\ B_s B_s^*,\ B_s^* B_s^*$
$\Upsilon(1S)\pi\pi,\ \Upsilon(2S)\pi\pi,\ \Upsilon(3S)\pi\pi$



To move from $\Upsilon(4S) \rightarrow \Upsilon(5S)$ ($\sqrt{s}=10579 \rightarrow \sqrt{s}=10870$), increase beam energies by 2.7%

Belle $\Upsilon(5S)$ data:

June 2005: 1.86 fb^{-1}	fall 2008: 28.2 fb^{-1}
June 2006: 21.7 fb^{-1}	spring 2009: 53.2 fb^{-1}
Dec. 2007: 7.9 fb^{-1}	fall 2009: 23.7 fb^{-1}

TOTAL: 129 fb^{-1}

Other (world) $\Upsilon(5S)$ data:

1985: CLEO,CUSB:	0.1 fb^{-1}
2003: CLEO III:	0.42 fb^{-1}
2008: BaBar:	0.7 fb^{-1}

$N = (129\ fb^{-1}) \times (0.302\ nb) \times (0.193) \times 2 =$ **15 x 10^6 B_s decays**

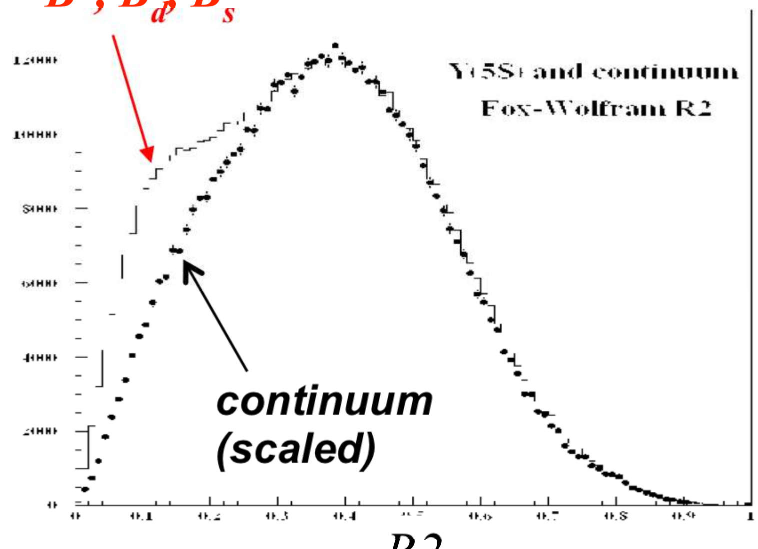
↑ **Belle sample** ↑ $\sigma[e^+e^- \rightarrow \Upsilon(5S)]$ ↑ $\mathcal{B}[\Upsilon(5S) \rightarrow B_s^{(*)} B_s^{(*)}]$

$b\bar{b}$ production at the $\Upsilon(5S)$

June 2005:

- *first did energy scan at five points: E = 10.825, 10.845, 10.865, 10.885, 10.905 GeV, about 0.030 fb^{-1} each point*
- *shifted to E=10.869 GeV (nominal peak), took 1.86 fb^{-1} of data*
- *by end of run, inst. Lum. = 1.4 x 10^{34} cm^{-2} s^{-1} (like Υ(4S) running)*

Fox-Wolfram moment R2:



$$\sigma_{b\bar{b}}^{\Upsilon(5S)} = \frac{N_{b\bar{b}}^{\Upsilon(5S)}}{\mathcal{L}_{\Upsilon(5S)} \cdot \varepsilon_{b\bar{b}}^{\Upsilon(5S)}}$$

where:

$$N_{b\bar{b}}^{\Upsilon(5S)} = N_{\rm hadronic}^{\Upsilon(5S)} - N_{\rm hadronic}^{\rm continuum} \cdot \left(\frac{\mathcal{L}_{\Upsilon(5S)}}{\mathcal{L}_{\rm continuum}}\right) \left(\frac{E_{\Upsilon(5S)}}{E_{\rm continuum}}\right)^2 \left(\frac{\varepsilon_{\Upsilon(5S)}}{\varepsilon_{\rm continuum}}\right)$$

Result:

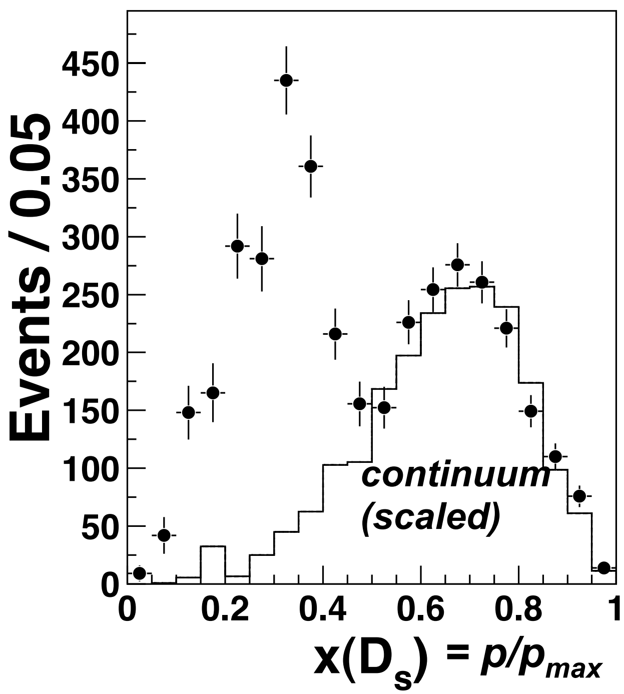
$$\sigma_{b\bar{b}}^{\Upsilon(5S)} = (0.302 \pm 0.015)\ \text{nb}$$

Drutskoy et al., PRL98, 052001 (2007)

Υ(5S) production; how many B_s decays?

Fraction of B_sB_s production determined by measuring inclusive D_s rate (branching fraction):

$$\underbrace{\frac{\mathcal{B}(\Upsilon(5S)\to D_s X)}{2}}_{\text{measured}} = f_s \cdot \underbrace{\mathcal{B}(B_s \to D_s X)}_{\text{theoretically estimated}} + (1-f_s)\cdot \underbrace{\mathcal{B}(B \to D_s X)}_{\text{measured by BaBar}}$$



must estimate:

$\mathcal{B}(B_s \to D_s X) = (92 \pm 11)\%$ *(hep- ex/0508047 CLEO)*

other inputs:

$\mathcal{B}(B \to D_s X) = (8.94 \pm 0.16 \pm 1.12)\%$ *(BaBar)*

$\mathcal{B}(D_s \to \phi\, \pi^+) = (4.5 \pm 0.4)\%$ *(dominant systematic)*

Result:

$$f_s = (19.3 \pm 2.9)\%$$

PDG 2009

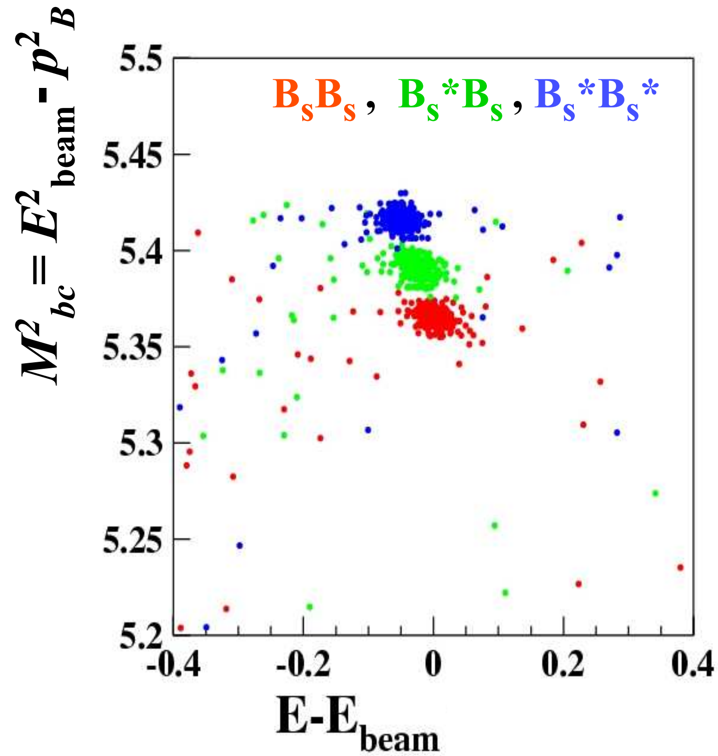
[method pioneered by CLEO: (16.0 ± 2.6 ± 5.8)%]

$\Upsilon(5S)$ production; how many B_s decays?

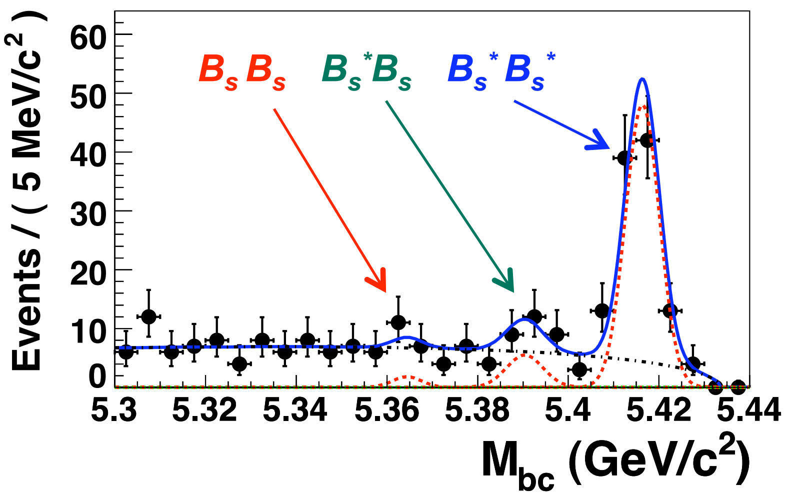
Three processes: $e^+e^- \to B_s^*B_s^*,\ B_s^*B_s,\ B_sB_s$

As we do not reconstruct the γ in $B_s^* \to B_s\gamma$, these production mechanisms are separated in M_{bc}-ΔE space:

$$M_{bc} \equiv \sqrt{E^2_{\rm beam} - p^2_B}$$
$$\Delta E \equiv E_B - E_{\rm beam}$$



Fraction of $B_s^*B_s^*$ production determined by measuring $B_s \to D_s\,\pi^+$ decays:



Result:

$$f(B_s^*B_s^*) = (90.1\,^{+3.8}_{-4.0} \pm 0.2)\%$$
$$f(B_s^*B_s) = (7.3\,^{+3.3}_{-3.0} \pm 0.1)\%$$

Louvot et al., PRL102, 021801 (2009)

B_s analyses, results

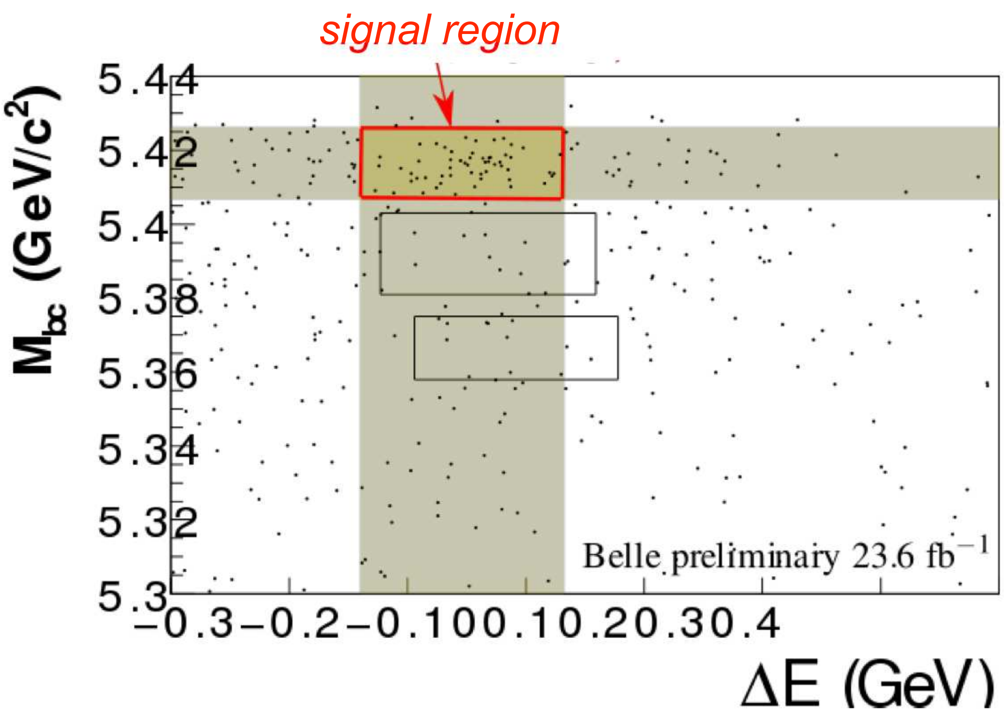
$\Upsilon(5S) \to D_s^+ X, D^0 X$ (inclusive) $J/\psi X$ (inclusive)	1.86 fb^{-1}	*Drutskoy et al., PRL 98, 052001 (2007)*
$B_s \to D_s^{(*)} \pi^+, D_s^{(*)} \rho^+$ $J/\psi \phi, J/\psi \eta$	1.86 fb^{-1}	*Drutskoy et al., PRD 76, 012002 (2007)*
$B_s \to \phi \gamma, \gamma\gamma$ (upper limit)	23.6 fb^{-1}	*Wicht et al., PRL 100, 121801 (2008)*
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-, \Upsilon(1S)K^+K^-,$ $\Upsilon(2S)\pi^+\pi^-, \Upsilon(3S)\pi^+\pi^-$	21.7 fb^{-1}	*Chen et al., PRL 100, 112001 (2008)*
$B_s \to D_s \pi^+, D_s K^+$	23.6 fb^{-1}	*Louvot et al., PRL 102, 021801 (2009)*
$B_s \to D_s^* \pi^+,$ $D_s^{(*)} \rho^+$ (with polarization)	23.6 fb^{-1}	*Louvot et al., PRL 104, 231801 (2010)*
$B_s \to K^+K^-, K_S K_S, K^-\pi^+, \pi^+\pi^-$	23.6 fb^{-1}	*Peng et al., arXiv:1006.5115, submitted to PRD*
$B_s \to J/\psi \eta, J/\psi \eta'$	23.6 fb^{-1}	*Li (Hawaii), arXiv:0912.1434*
$B_s \to D_s^{(*)} D_s^{(*)}$	23.6 fb^{-1}	*Esen, et al., arXiv:1005.5177, submitted to PRL*
$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-, \Upsilon(2/3S)\pi^+\pi^-$	8.2 fb^{-1}	*Chen et al., , arXiv:0808.2445, submitted to PRD*
$\Upsilon(5S) \to BB\pi, BB\pi\pi$	23.6 fb^{-1}	*Drutskoy et al., PRD 81, 112003(R) (2010)*

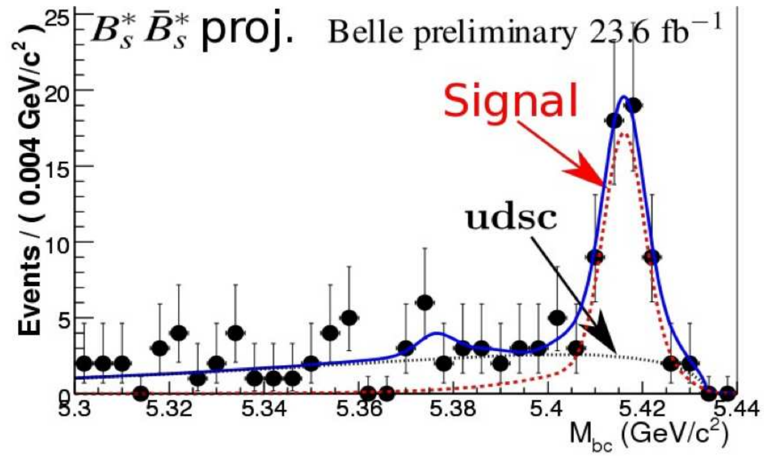
$B_s \rightarrow D_s^{(*)}\rho^+$ (Cabibbo-favored)

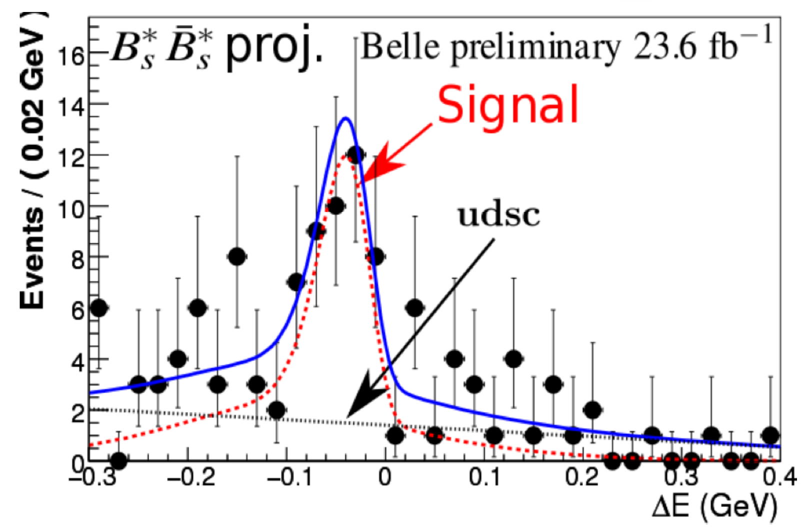
23.6 fb^{-1}: R. Louvot

$B_s \rightarrow D_s^{*}\rho^+$:

$$M_{bc} \equiv \sqrt{E_{\rm beam}^2 - p_B^2}$$
$$\Delta E \equiv E_B - E_{\rm beam}$$







Background from continuum only
~73 signal events are observed
in the $B_s^*B_s^*$ region (8.6σ)

First observation!

$$\mathcal{B}(B_s^0 \rightarrow D_s^{*-}\rho^+) = (13.0^{+2.3}_{-2.1}(\text{stat.})\pm 1.7(\text{syst.})\pm 1.7(\text{pol.})\pm 1.9(f_s))10^{-3}$$

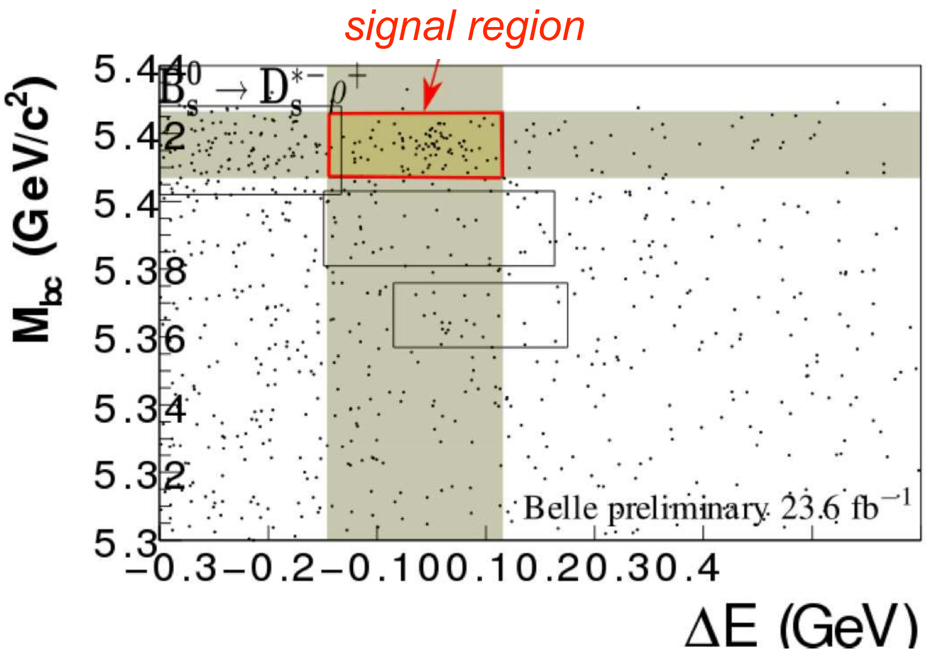
$B_s \to D_s^{(*)}\rho^+$ (Cabibbo-favored)

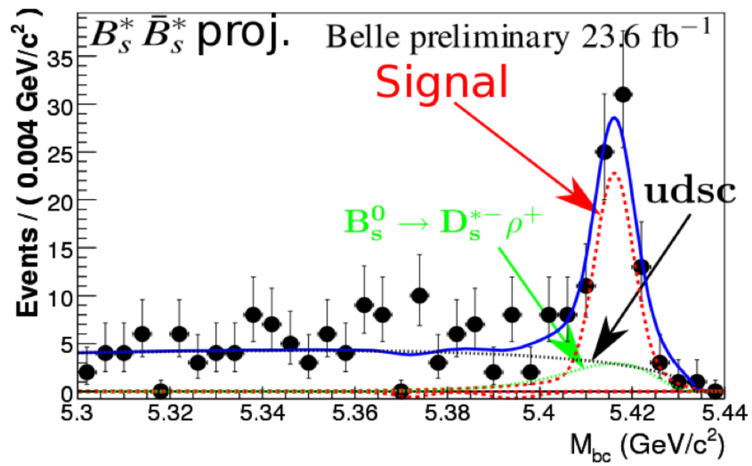
23.6 fb^{-1}: R. Louvot

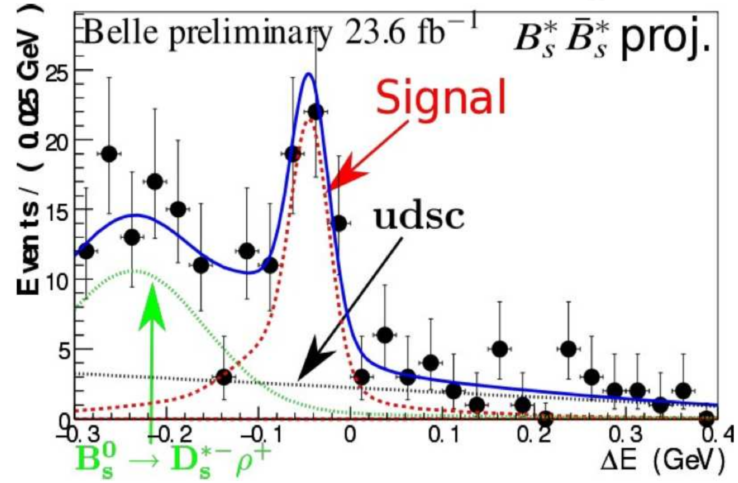
$$M_{bc} \equiv \sqrt{E_{\rm beam}^2 - p_B^2}$$
$$\Delta E \equiv E_B - E_{\rm beam}$$

$B_s \to D_s\,\rho^+$:

signal region







Background from $B_s \to D_s^*\,\rho^+$
~87 signal events are observed in the $B_s^*B_s^*$ region (10.1σ)

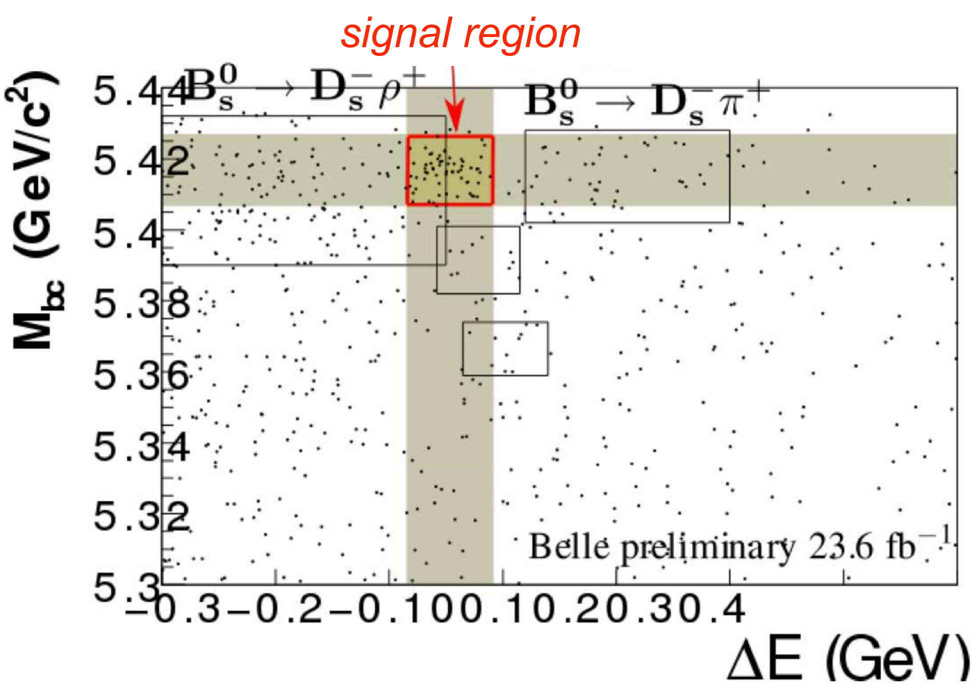
First observation!

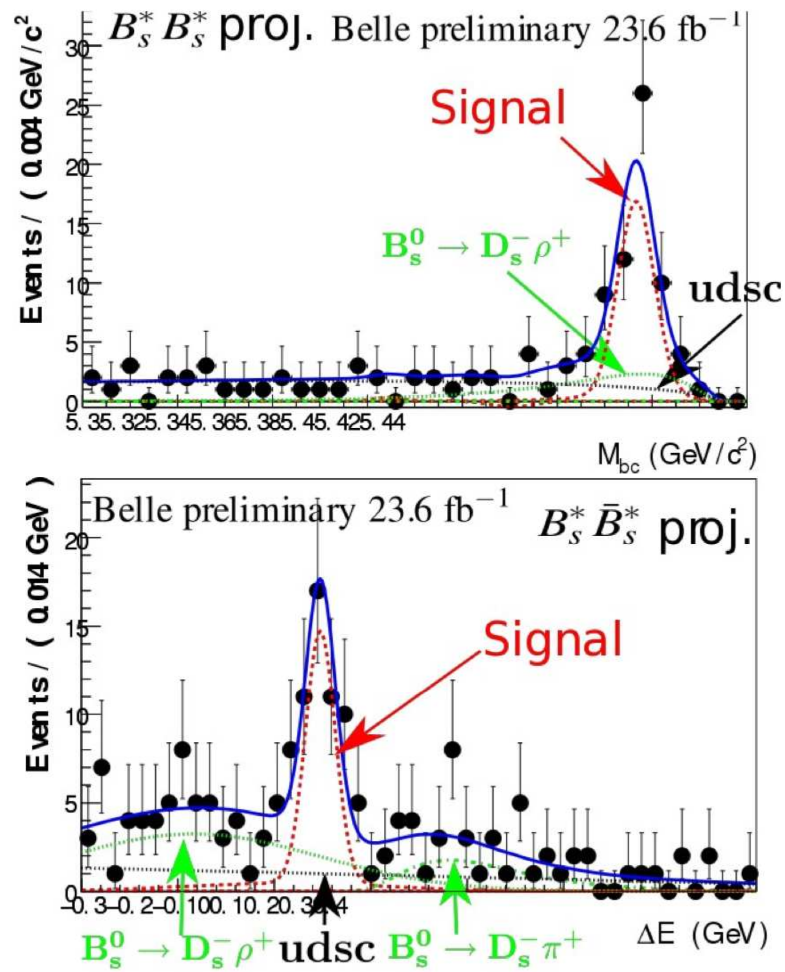
$$\mathcal{B}(B_s^0 \to D_s^-\rho^+) = (8.5^{+1.3}_{-1.2}(\text{stat.}) \pm 1.1(\text{syst.}) \pm 1.3(f_s)) \times 10^{-3}$$

$B_s \to D_s^{*}\pi^+$ (Cabibbo-favored)

23.6 fb^{-1}: R. Louvot

$$M_{bc} \equiv \sqrt{E_{\rm beam}^2 - p_B^2}$$
$$\Delta E \equiv E_B - E_{\rm beam}$$





Background from $B_s \to D_s \pi^+$ and $D_s \rho^+$
~54 signal events are observed
in the $B_s^* B_s^*$ region (8.4σ)

First observation!

$$\mathcal{B}(B_s^0 \to D_s^{*-}\pi^+) = (2.4^{+0.5}_{-0.4}(\text{stat.}) \pm 0.3(\text{syst.}) \pm 0.4(f_s)) \times 10^{-3}$$

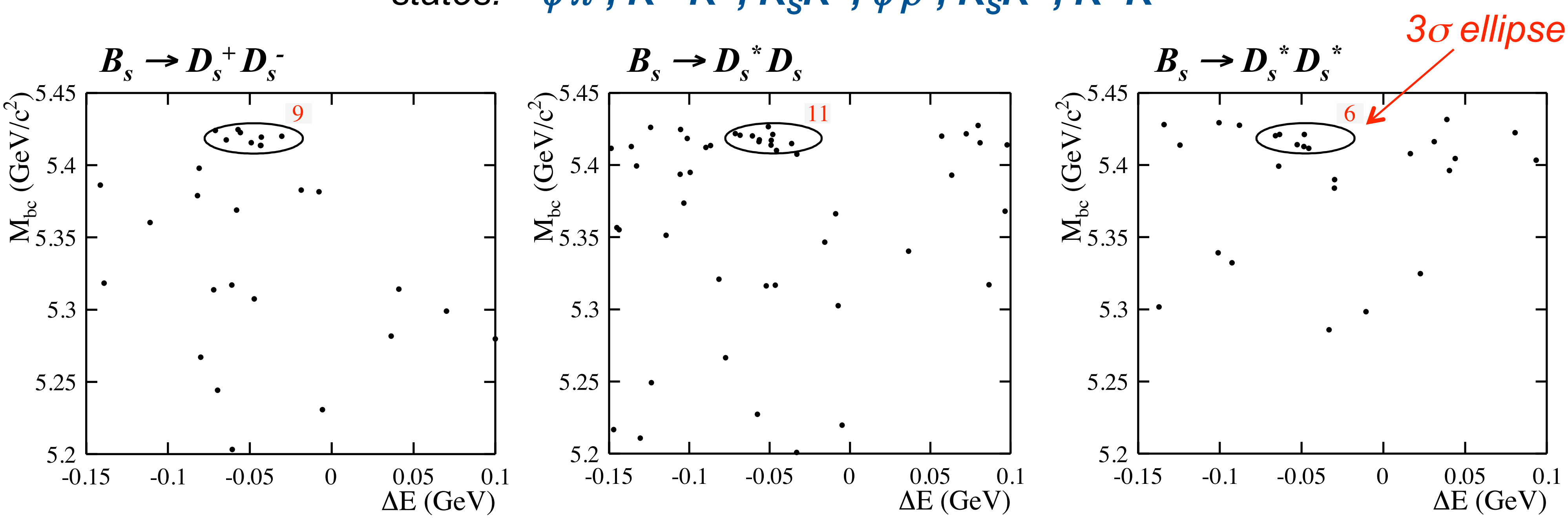
$B_s \to D_s^{(*)}D_s^{(*)}$ (Cabibbo-favored)

Esen, Schwartz, arXiv:1005.5177

In Shifman-Voloshin limit **(M_b,$M_c \to \infty$, $M_b \to 2M_c$)**, *the partial widths of (Cabibbo-favored) $B_s \to D_s^{*+}D_s^{(*)-}$ are CP-even and will dominate the decay width difference between B_s-B_s mass eigenstates.* Aleksan et al., PLB 316, 567 (1993)

⇒ *Measuring the branching fraction constrains $\Delta\Gamma_s/\Gamma_s$, which is an important mixing parameter in the B_s system. Our results are competitive with, and complementary to, those of CDF/D0.*

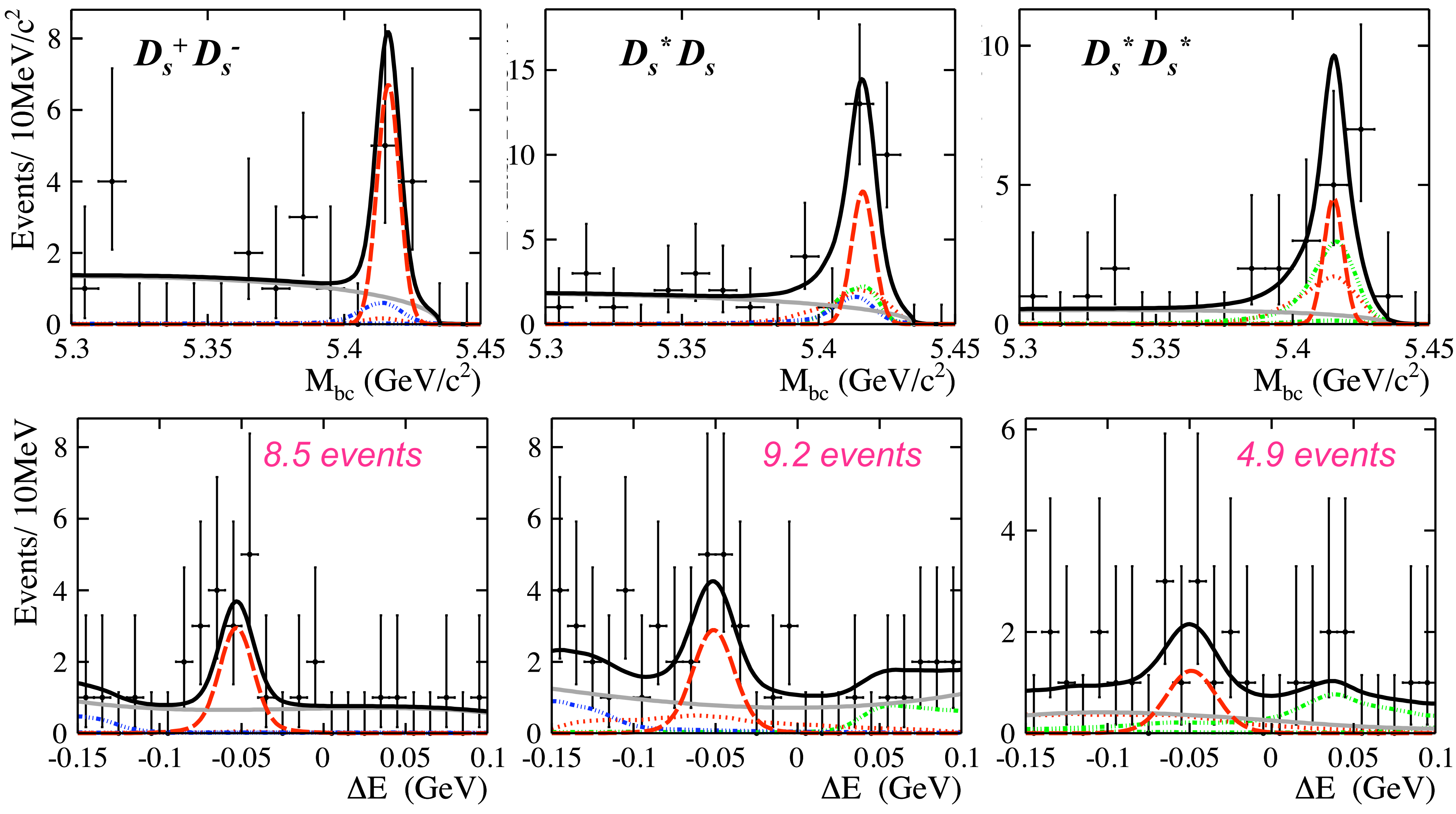
23.6 fb^{-1}: We reconstruct $D_s^{*+} \to D_s^+\gamma$. To maximize sensitivity, reconstruct 6 D_s final states: $\phi\pi^+$, $K^{*0}K^+$, K_SK^+, $\phi\rho^+$, K_SK^{*+}, $K^{*0}K^{*+}$



$B_s \to D_s^{(*)} D_s^{(*)}$ cont'd

Esen, Schwartz, arXiv:1005.5177

Two-dimensional fit for event yields: *fix cross-feed down to MC, float cross-feed up*



$B_s \to D_s^{(*)} D_s^{(*)}$ cont'd

Esen, Schwartz, arXiv:1005.5177

Fit results:

Mode	Y (events)	ε ($\times 10^{-4}$)	$\mathcal{B}$ (%)	S
$D_s^+ D_s^-$	$8.5\,^{+3.2}_{-2.6}$	3.31	$1.03\,^{+0.39}_{-0.32}\,^{+0.15}_{-0.13} \pm 0.21$	6.2
$D_s^{*\pm} D_s^{\mp}$	$9.2\,^{+2.8}_{-2.4}$	1.35	$2.75\,^{+0.83}_{-0.71} \pm 0.40 \pm 0.56$	6.6
$D_s^* D_s^*$	$4.9\,^{+1.9}_{-1.7}$	0.643	$3.08\,^{+1.22}_{-1.04}\,^{+0.57}_{-0.58} \pm 0.63$	3.1
Sum	$22.6\,^{+4.7}_{-3.9}$		$6.85\,^{+1.53}_{-1.30} \pm 1.11\,^{+1.40}_{-1.41}$	

$$S = \sqrt{-2\ln\left(\frac{\mathcal{L}_0}{\mathcal{L}_{\max}}\right)}$$

"External" systematic errors (to be measured better with more data)

$B_s \rightarrow D_s^{(*)} D_s^{(*)}$ cont'd

Esen, Schwartz, arXiv:1005.5177

Systematic errors:

Source	$D_s^+ D_s^-$		$D_s^{*\pm} D_s^{\mp}$		$D_s^{*+} D_s^{*-}$	
	$+\sigma$	$-\sigma$	$+\sigma$	$-\sigma$	$+\sigma$	$-\sigma$
CR PDF shape	0.8	0.8	0.3	0.3	0.5	0.4
Background PDF	1.1	1.3	1.9	2.0	3.0	6.1
WC+CF PDF	0.3	0.3	1.5	1.5	4.4	4.4
WC/CF fractions	0.2	0.2	5.0	5.0	8.7	8.7
$\mathcal{R}$ requirement ($q\bar{q}$ suppr.)	1.8	1.8	1.8	1.8	1.8	1.8
Best candidate selection	6.9	0.0	2.2	0.0	2.2	0.0
$K^\pm$ identification	10.1	10.1	10.6	10.6	10.9	10.9
K_S^0	2.1	2.1	2.1	2.1	2.2	2.2
π^0	1.1	1.1	1.1	1.1	1.0	1.0
γ	-	-	3.8	3.8	7.6	7.6
Tracking	6.2	6.2	6.2	6.2	6.2	6.2
Polarization	0.2	0.0	0.8	0.5	0.7	0.3
MC statistics for ε	1.1	1.1	0.9	0.8	1.0	1.0
$D_s^{(*)}$ BF's	12.4	12.4	12.4	12.4	12.5	12.5
Luminosity	± 1.3					
$\sigma_{\Upsilon(5S)}$	± 4.6					
f_s	± 15					
$f_{B_s^* \overline{B}_s^*}$	$^{+4.2}_{-4.4}$					
Total	24.9	24.0	25.1	25.1	27.5	28.0

"External" systematic errors (to be measured better with more data)

$B_s \to D_s^{(*)} D_s^{(*)}$ cont'd

Esen, Schwartz, arXiv:1005.5177

Relationship between branching fraction and $\Delta\Gamma/\Gamma$:

Neglect CPV:

$$\begin{aligned}
\mathcal{B}(B_s \to D_s D_s) &= \left(\frac{1}{2}\right) \mathcal{B}(B_{s+} \to D_s D_s) \\
&= \left(\frac{1}{2}\right) \frac{\Gamma(B_{s+} \to D_s D_s)}{\Gamma_+} \\
&= \left(\frac{1}{2}\right) \frac{\Delta\Gamma}{\Gamma + \Delta\Gamma/2} \\
\Rightarrow \quad 2\mathcal{B} &= \frac{\Delta\Gamma/\Gamma}{1 + \Delta\Gamma/(2\Gamma)} \\
\Rightarrow \quad \frac{\Delta\Gamma}{\Gamma} &= \frac{2\mathcal{B}}{1 - \mathcal{B}}
\end{aligned}$$

Result:

$$\frac{\Delta\Gamma}{\Gamma} = 0.147\,^{+0.036}_{-0.030}\,^{+0.042}_{-0.041}$$

Compare to 2010 PDG:
$\Delta\Gamma_s/\Gamma_s = 0.092\,^{+0.051}_{-0.054}$

$B_s \rightarrow D_s^{(*)} D_s^{(*)}$ cont'd

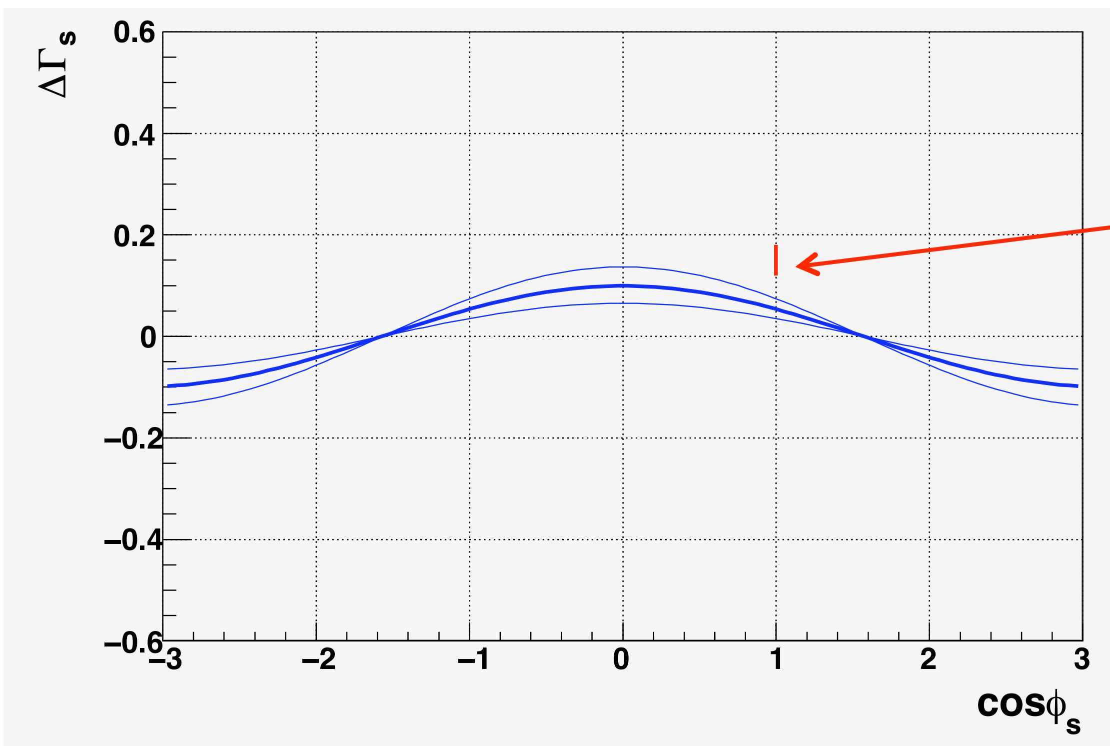
Esen, Schwartz, arXiv:1005.5177

Relationship between branching fraction and $\Delta\Gamma/\Gamma$:

Include CPV: *Dunietz, Fleischer, Nierste, PRD 63, 114015 (2001)*

$$4\,\mathcal{B}(B_s \rightarrow D_s D_s) = \left(\frac{\Delta\Gamma}{\cos\varphi}\right)\left[\frac{1+\cos\varphi}{1+\Delta\Gamma/2} + \frac{1-\cos\varphi}{1-\Delta\Gamma/2}\right]$$

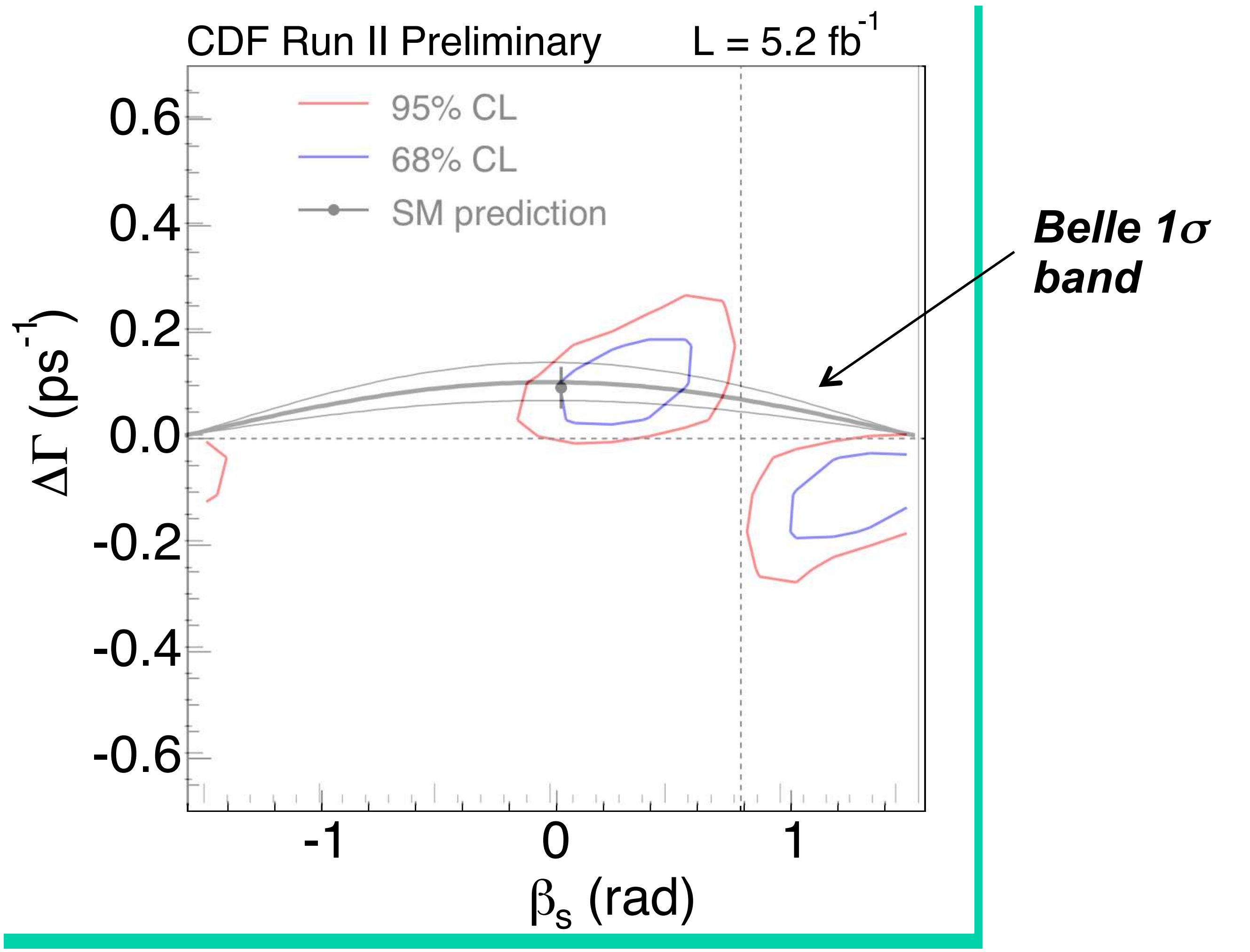
$$\text{where } \varphi = \text{Arg}\left(\frac{M_{12}}{\Gamma_{12}}\right)$$



$B_s \to D_s^{(*)} D_s^{(*)}$ cont'd

Esen, Schwartz, arXiv:1005.5177

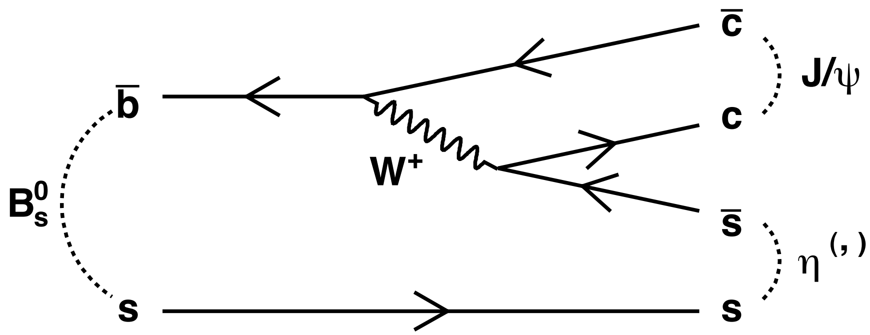
Compare to CDF/D0:

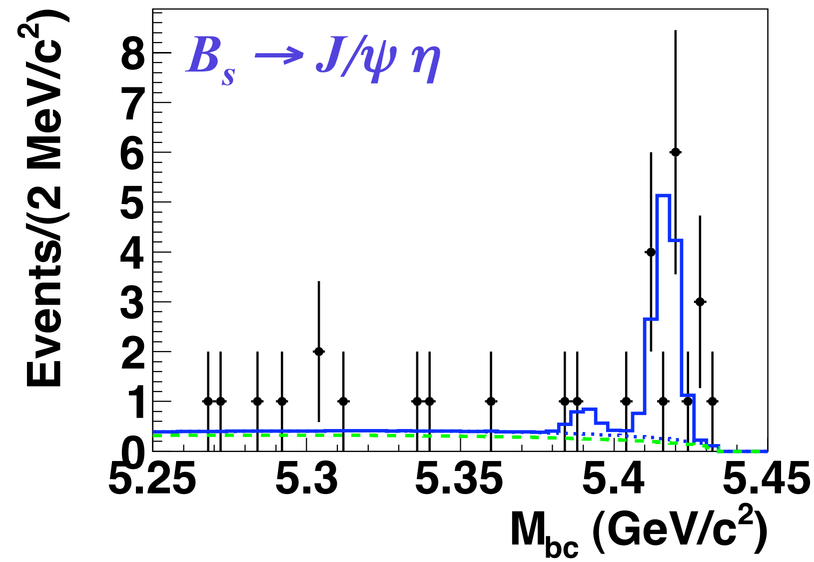


More CP eigenstates: $B_s \to J/\psi\, \eta$, $J/\psi\, \eta'$

23.6 fb^{-1}: J. Li et al., arXiv:0912.1434 (2009)

Analogous to $B^0 \to J/\psi\, K_S$:

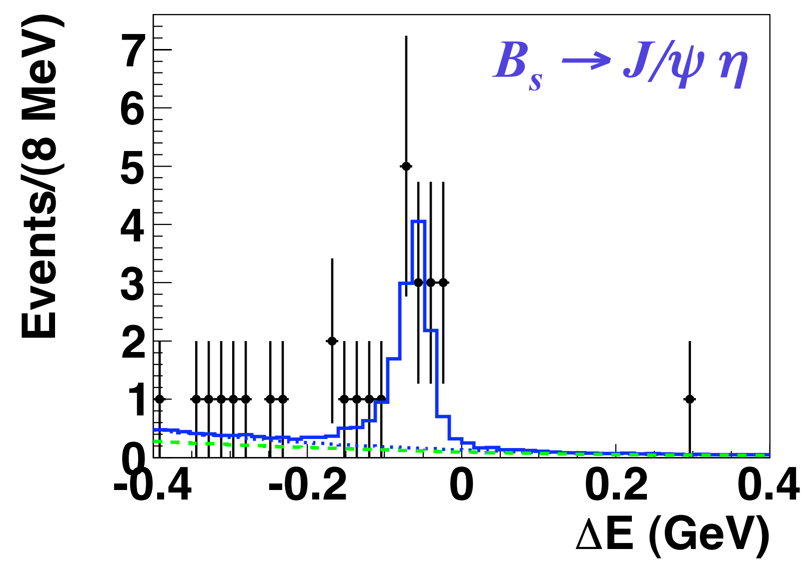




Reconstruct $J/\psi \to \mu^+\mu^-$, e^+e^-

$\eta \to \gamma\gamma$, $\pi^+\pi^-\pi^0$

$\eta' \to \eta\pi^+\pi^-$, $\rho^0\gamma$



$B_s \to J/\psi\, \eta$:

***N* = 14.9 ± 4.1**

$\mathcal{B}$ = (3.32 ±0.87± 0.32± 0.42) x 10^{-4}

7.3σ significance

More CP eigenstates: $J/\psi\ \eta$, $J/\psi\ \eta'$ cont'd

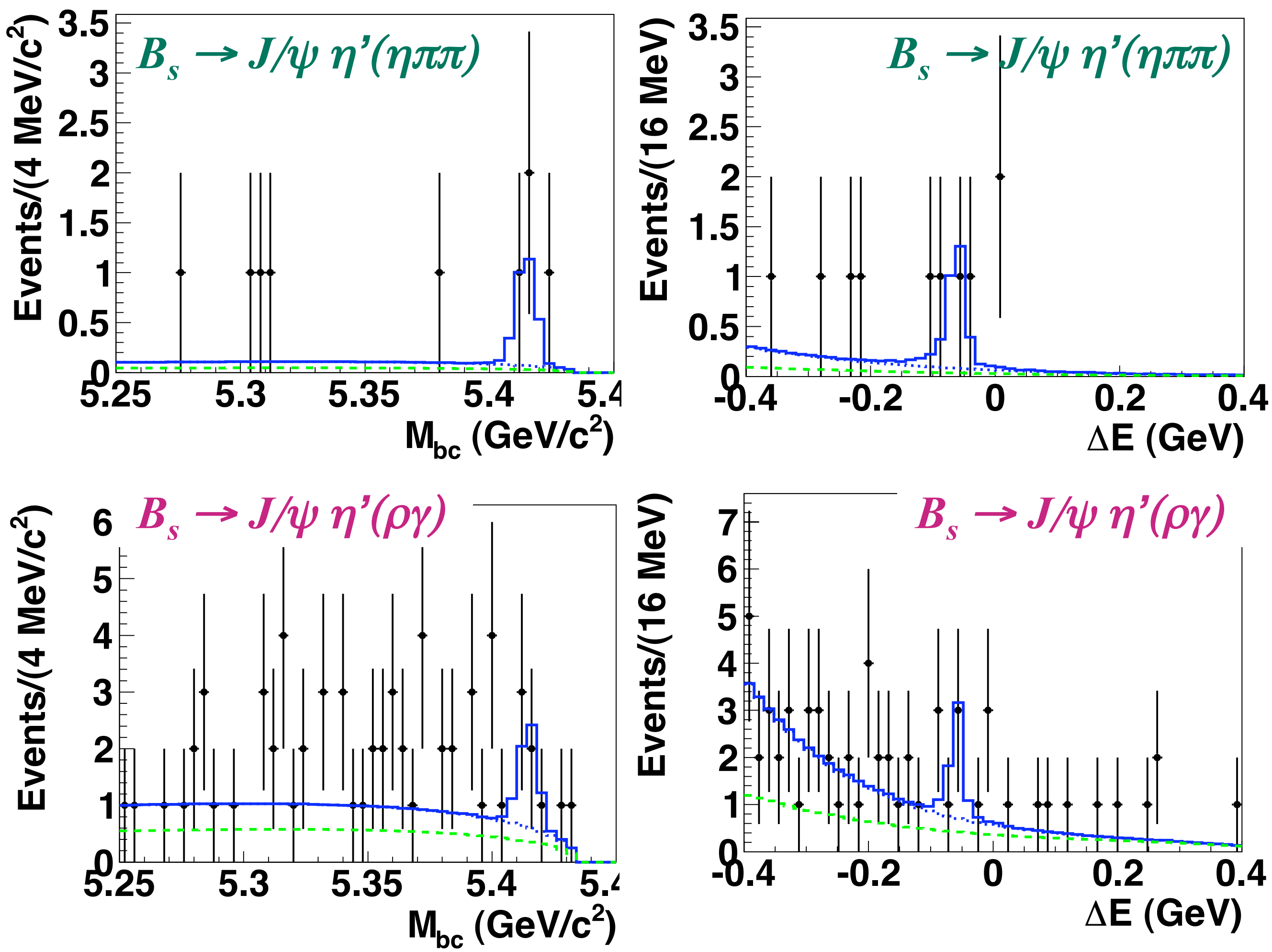
23.6 fb -1: Li et al., arXiv:0912.1434 (2009)

$B_s \to J/\psi\ \eta'$:

N = 10.7 ± 4.6

$\mathcal{B}$ = (3.1 ±1.2± 0.5± 0.4) x 10^{-4}

3.8σ significance



$B_s \to h_1 h_2$

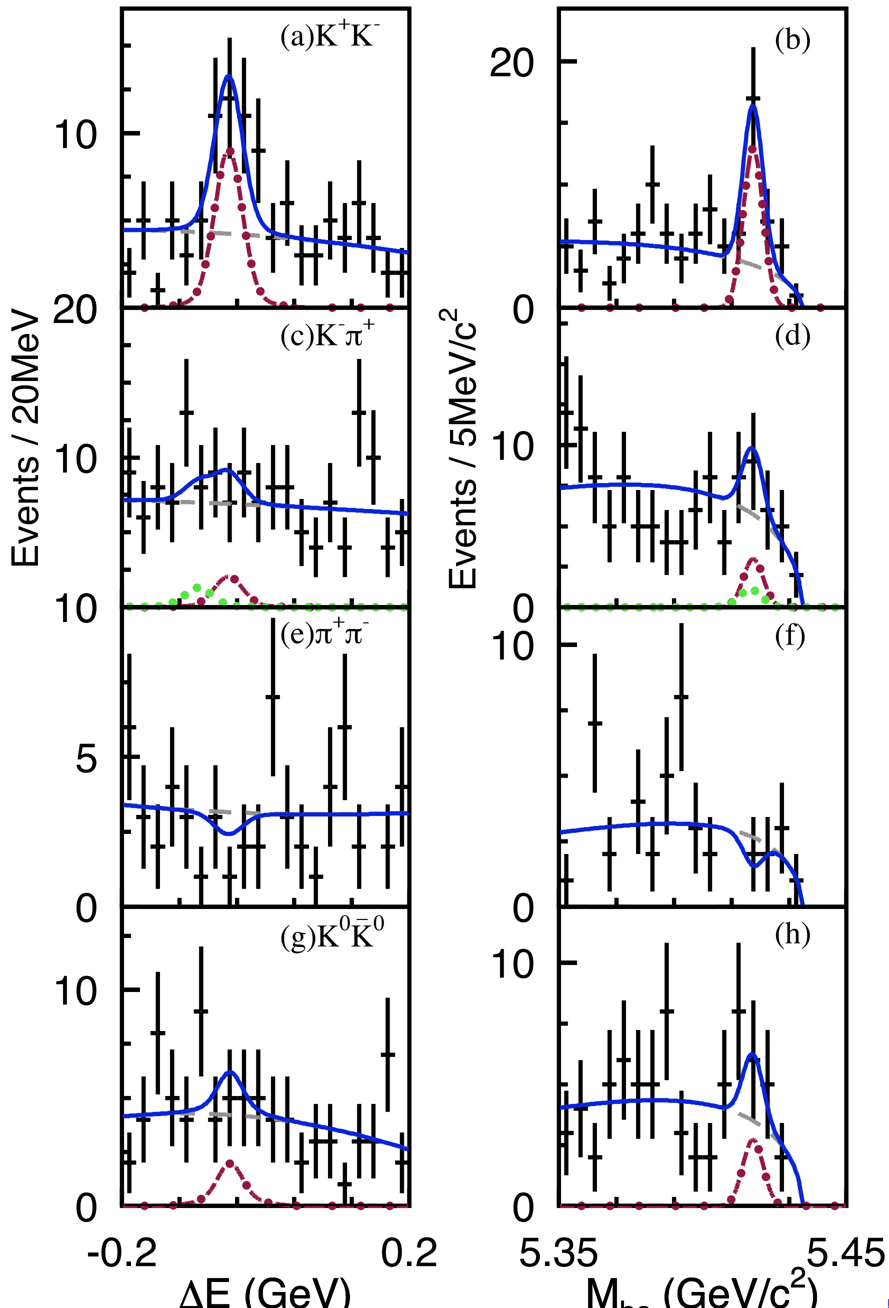
23.6 fb^{-1}: C.C. Peng, P. Chang

$B_s \to K^+ K^-$
(like $B^0 \to K^+ \pi^-$)

$B_s \to K^+ \pi^-$

$B_s \to \pi^+ \pi^-$

$B_s \to K^0 K^0$



$N = 23.4^{+5.5}_{-5.4}$

$\mathcal{B} = (3.8 \pm 1.0 \pm 0.5 \pm 0.5) \times 10^{-5}$

5.8σ significance

$\mathcal{B} < 2.6 \times 10^{-5}$ (90% CL)

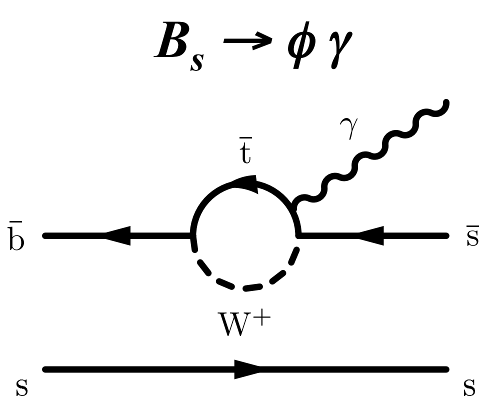
$\mathcal{B} < 1.2 \times 10^{-5}$ (90% CL)

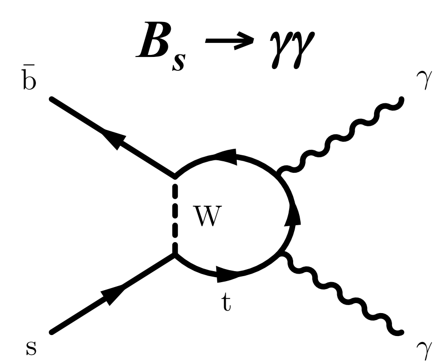
$\mathcal{B} < 6.6 \times 10^{-5}$ (90% CL)

$B_s \rightarrow \phi\,\gamma,\ \gamma\gamma$

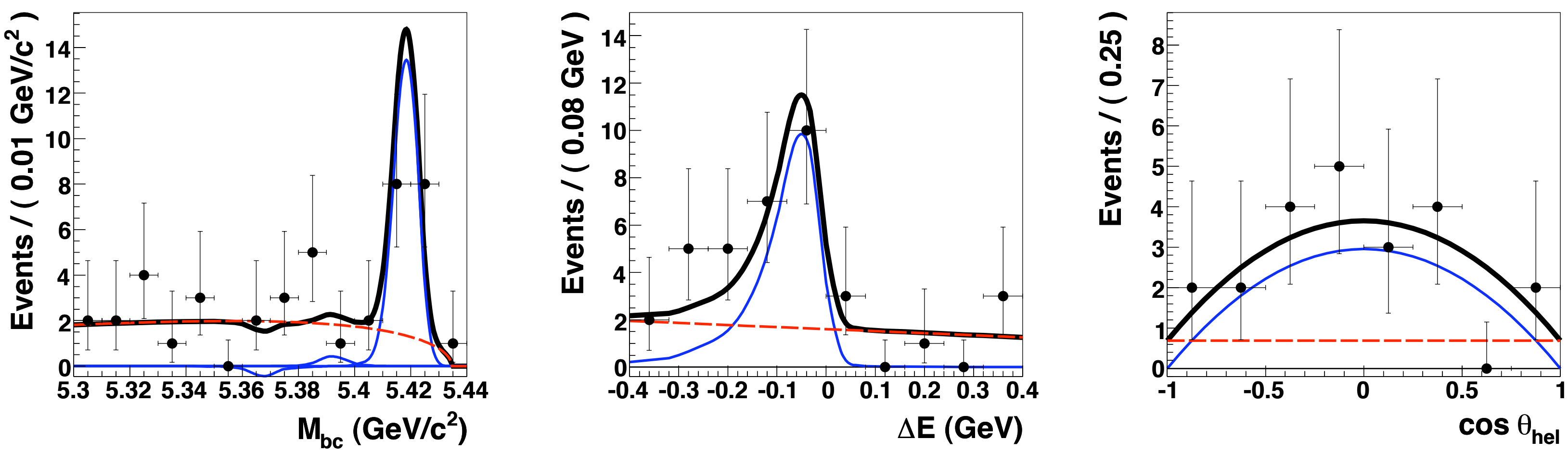
23.6 fb -1: Wicht et al., PRL 100, 121801 (2008)

Modes proceed via loops ⇒ sensitive to new physics





$B_s \rightarrow \phi\,\gamma$: main background from $B_s \rightarrow \phi\,\eta$, obtain signal yield via 3d fit to M_{bc}, ΔE, $\cos\theta_h$

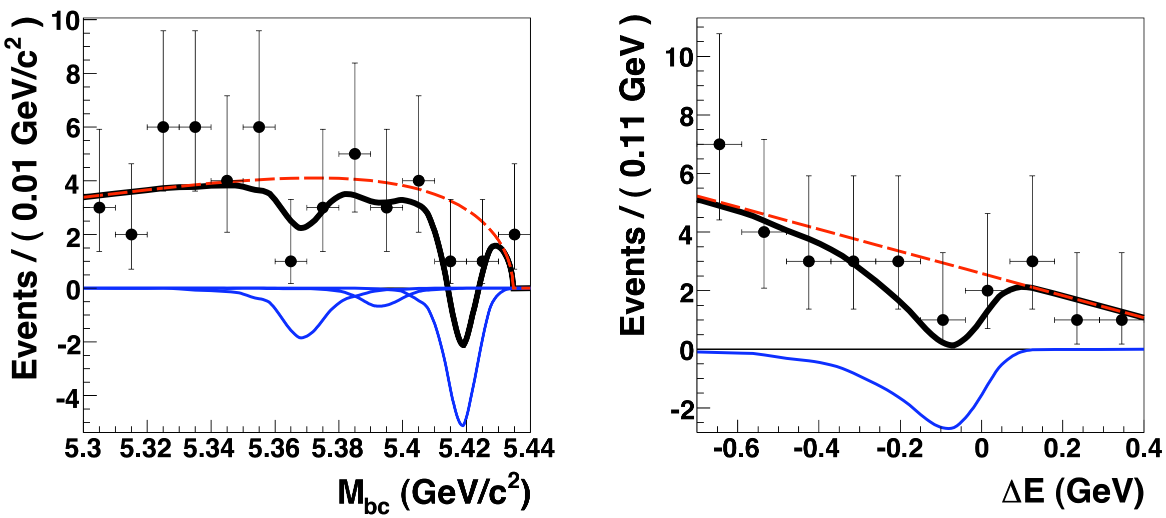


$N = 18^{+6}_{-5}$ $\quad$ $B = (5.7\,^{+1.8}_{-1.5}\,^{+1.2}_{-1.1}) \times 10^{-5}$ $\quad$ 5.5σ significance $\quad$ FIRST OBSERVATION

$B_s \to \phi\gamma$, $\gamma\gamma$, *cont'd*

23.6 fb -1: Wicht et al., PRL 100, 121801 (2008)

$B_s \to \gamma\gamma$: require γ's in barrel to reject $e^+e^- \to e^+e^-\gamma\gamma$, signal yield from 2d fit to M_{bc}, ΔE



Nothing observed:

$N = -7.3^{+2.4}_{-2.0}$	$B < 8.7 \times 10^{-6}$ (90% C.L.)	Previous PDG limit: $< 53 \times 10^{-6}$ SM prediction: $(0.5\text{-}1) \times 10^{-6}$

⇒ will very probably be observed at Belle II

$\Upsilon(5S) \rightarrow \Upsilon(1S)\pi^+\pi^-, \Upsilon(2S)\pi^+\pi^-, \Upsilon(3S)\pi^+\pi^-$

K.-F. Chen et al., PRL 100, 112001 (2008)

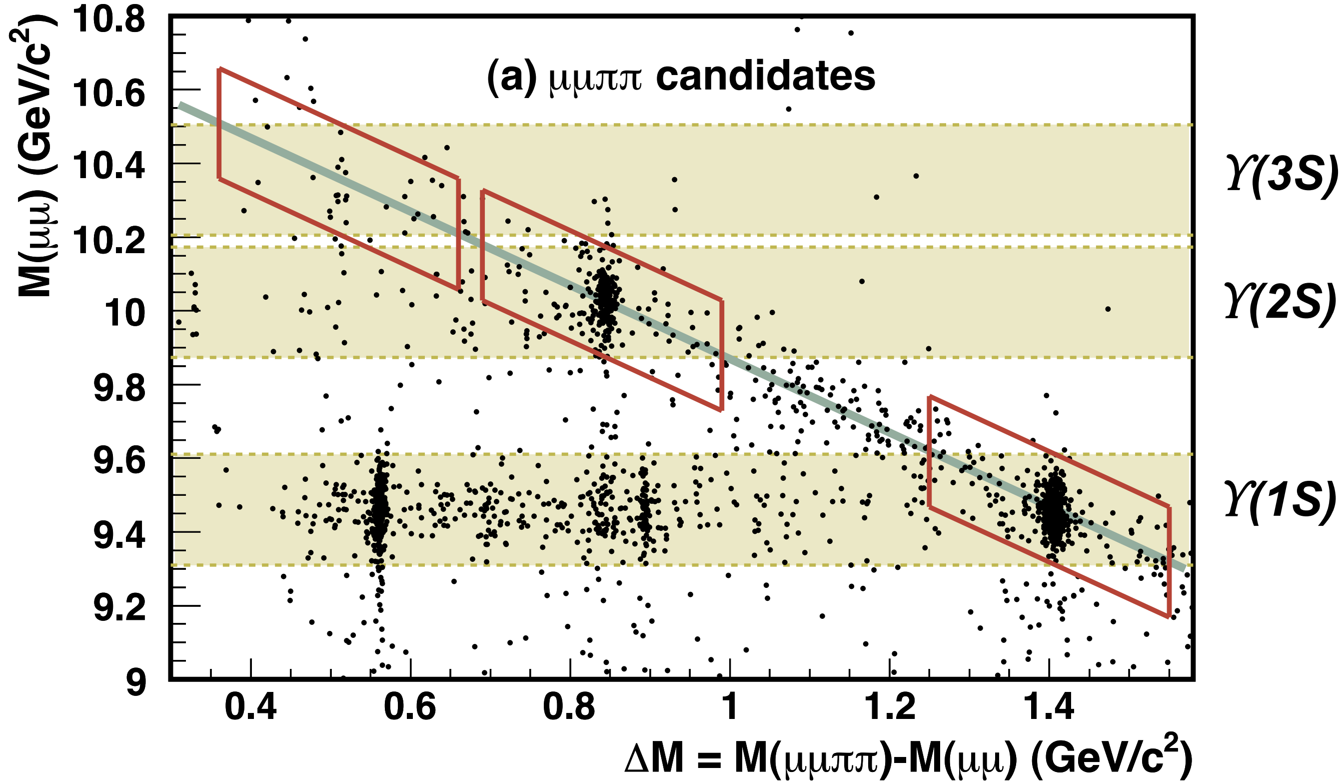
Motivation:

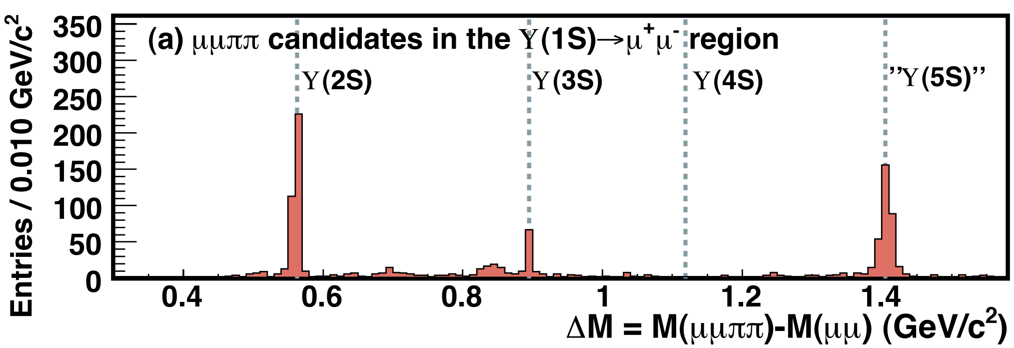
look for "Y_b" analog of $Y(4260) \rightarrow J/\psi\ \pi+\pi-$

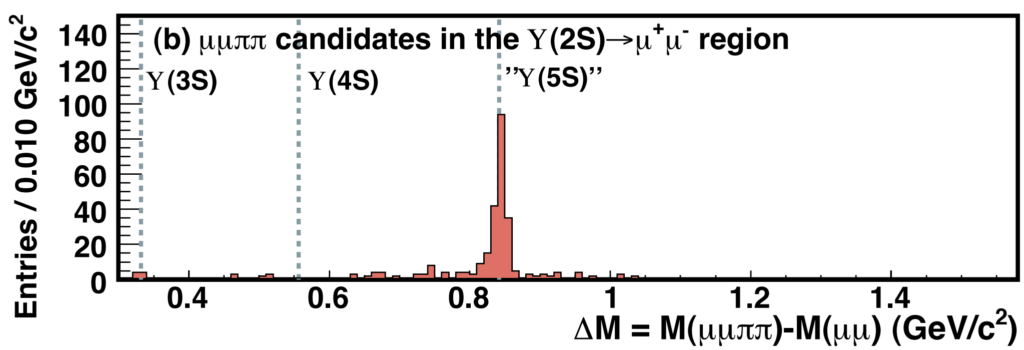
Select events:

$\Upsilon(5S) \rightarrow \Upsilon(nS)\ \pi^+\pi^-$

$\quad \hookrightarrow \mu^+\mu^-$







$\Upsilon(5S) \to \Upsilon(1S)\pi^+\pi^-, \Upsilon(2S)\pi^+\pi^-, \Upsilon(3S)\pi^+\pi^-$

Fit ΔM distribution to obtain event yields.
Results:

Using $\sigma(e^+e^-) \to \Upsilon(5S)$ = 0.302 ±0.015 nb

Using PDG value $\Gamma[\Upsilon(5S)]$ = 110 ±13 MeV

Process	σ(pb)	$\mathcal{B}$(%)	Γ(MeV)
$\Upsilon(1S)\pi^+\pi^-$	$1.61 \pm 0.10 \pm 0.12$	$0.53 \pm 0.03 \pm 0.05$	$0.59 \pm 0.04 \pm 0.09$
$\Upsilon(2S)\pi^+\pi^-$	$2.35 \pm 0.19 \pm 0.32$	$0.78 \pm 0.06 \pm 0.11$	$0.85 \pm 0.07 \pm 0.16$
$\Upsilon(3S)\pi^+\pi^-$	$1.44^{+0.55}_{-0.45} \pm 0.19$	$0.48^{+0.18}_{-0.15} \pm 0.07$	$0.52^{+0.20}_{-0.17} \pm 0.10$
$\Upsilon(1S)K^+K^-$	$0.185^{+0.048}_{-0.041} \pm 0.028$	$0.061^{+0.016}_{-0.014} \pm 0.010$	$0.067^{+0.017}_{-0.015} \pm 0.013$

Compare $\Upsilon(nS) \to \Upsilon(1S)$ transitions:

Process	Γ_{total}	$\Gamma_{e^+e^-}$	$\Gamma_{\Upsilon(1S)\pi^+\pi^-}$
$\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$	0.032 MeV	0.612 keV	0.0060 MeV
$\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$	0.020 MeV	0.443 keV	0.0009 MeV
$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$	20.5 MeV	0.272 keV	0.0019 MeV
$\Upsilon(10860) \to \Upsilon(1S)\pi^+\pi^-$	110 MeV	0.31 keV	0.59 MeV

> 100x larger

Follow-up analysis: $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-$

K.-F. Chen

Change beam energies, take more data, repeat ΔM fits (6 more points):

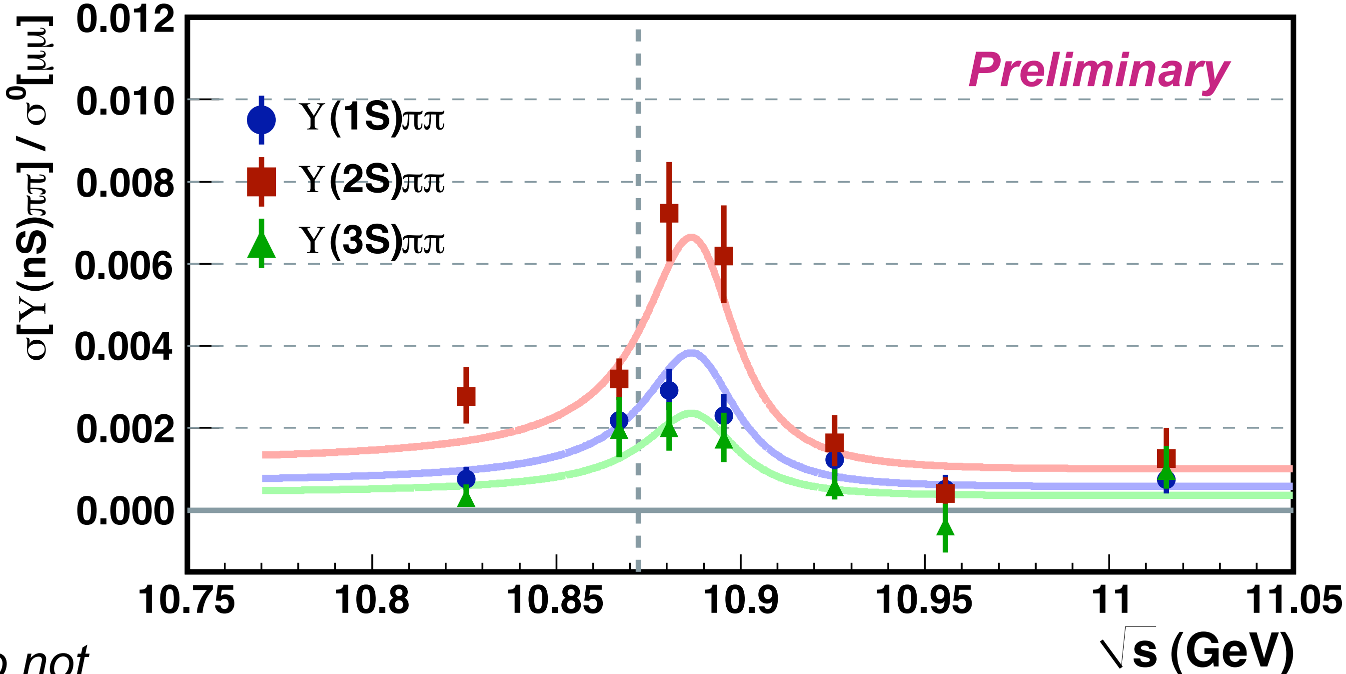
$\sqrt{s}$ = 10.8255, 10.8670, 10.8805, 10.8955, 10.9255, 10.9555, 11.0155 GeV

Results:

same large partial widths as before

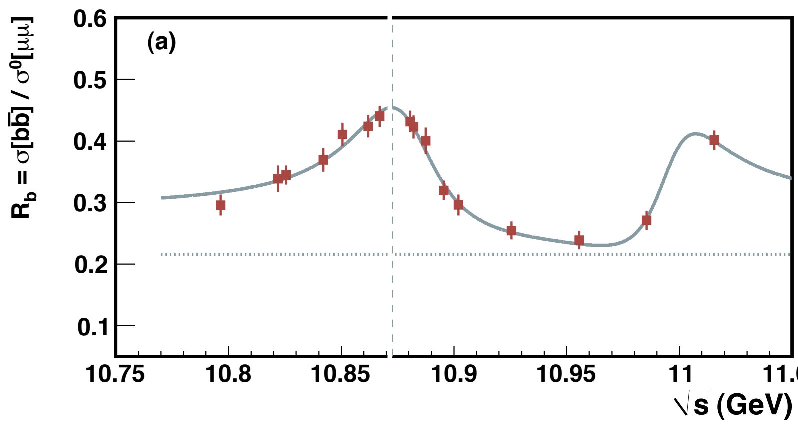
Fit to Breit-Wigners plus flat components:

μ = 10888.4 ± 2.7 ± 1.2 MeV
Γ = 30.7 ± 8.3 ± 3.1



Mass and width parameters do not correspond to those from energy scan data (30 pb^{-1} at 9 points):

μ = 10879 ± 3 MeV
Γ = 46 ± 9



BaBar, PRL 102, 012001 (2009):

μ = 10876 ± 2 MeV, Γ = 43 ± 4

Indication of a tetraquark state?
(Ali, arXiv:0911.2787, 0912.5016)

$\Upsilon(5S) \to B^{(*)}B^{(*)},\ B^{(*)}B^{(*)}\pi$

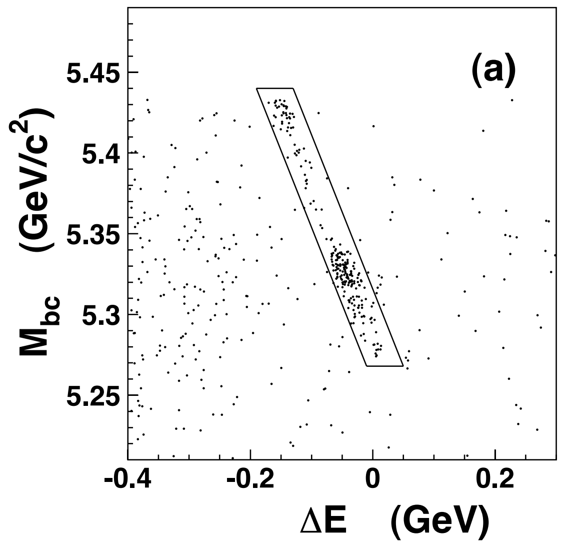
23 fb^{-1}: A. Drutskoy

Reconstruct 5 final states:

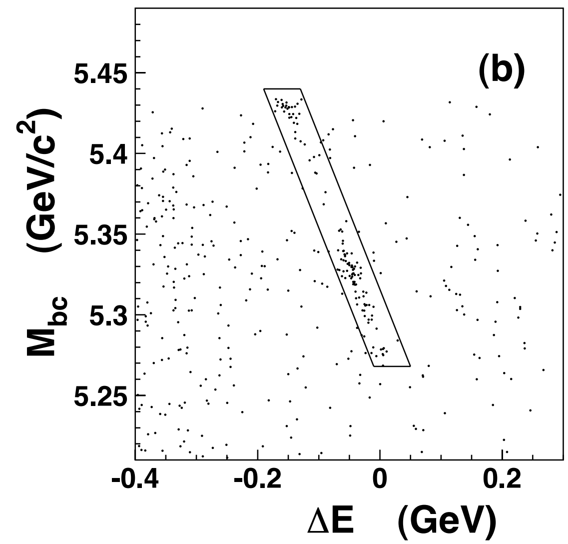
$$M_{bc} \equiv \sqrt{E_{\rm beam}^2 - p_B^2}$$
$$\Delta E \equiv E_B - E_{\rm beam}$$

2-body $B^{(*)}B^{(*)}$ and 3-body $B^{(*)}B^{(*)}\pi$ have different M_{bc}-ΔE shifts $\Rightarrow$ can fit for their yields

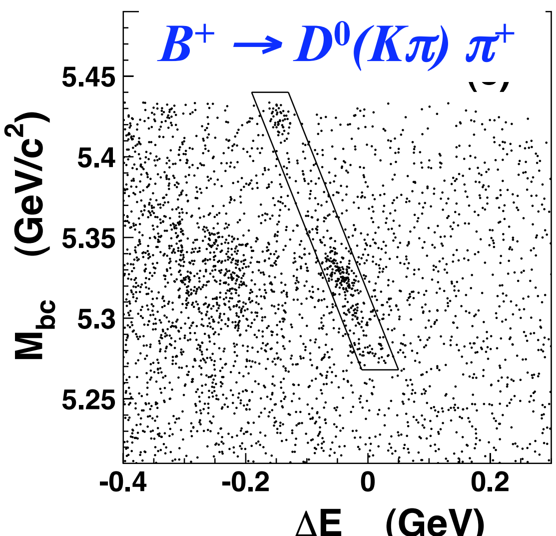
$B^+ \to J/\psi\ K^+$



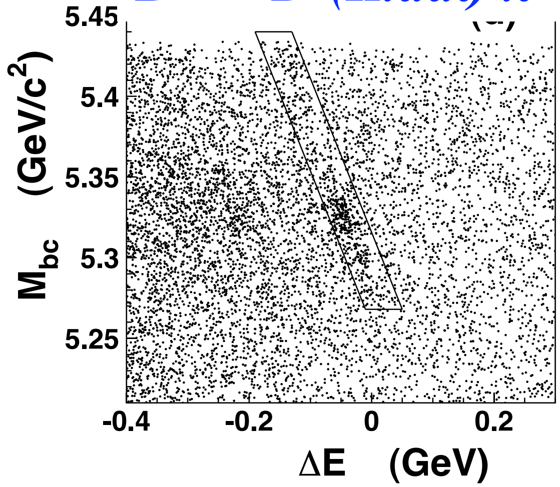
$B^0 \to J/\psi\ K^{*0}$



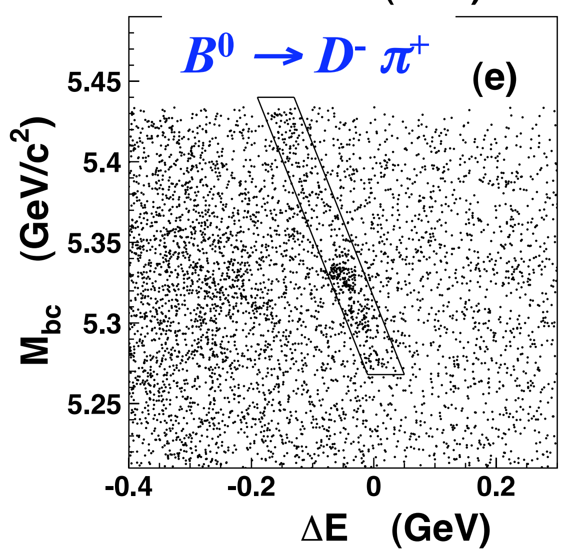
$B^+ \to D^0(K\pi)\ \pi^+$



$B^+ \to D^0(K\pi\pi\pi)\ \pi^+$

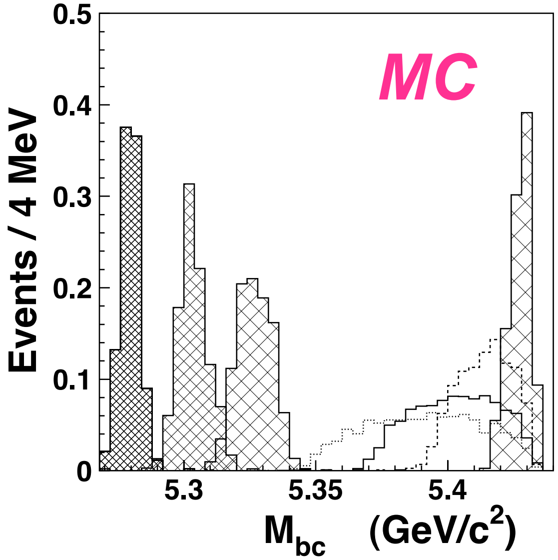


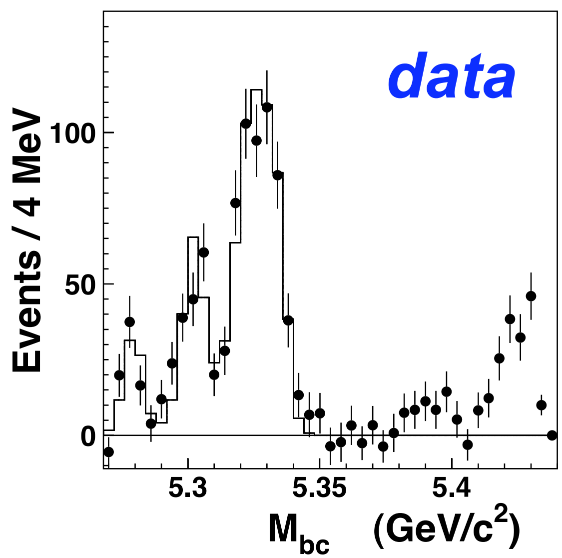
$B^0 \to D^-\ \pi^+$



$\Upsilon(5S) \to B^{(*)}B^{(*)}$, $B^{(*)}B^{(*)}\pi$, cont'd

Project onto M_{bc}:

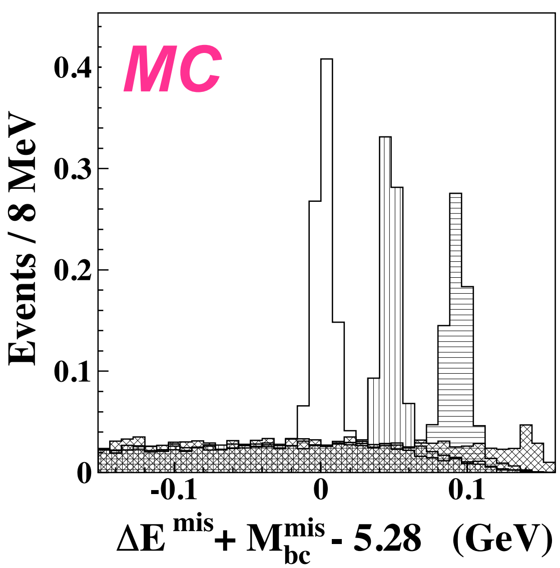


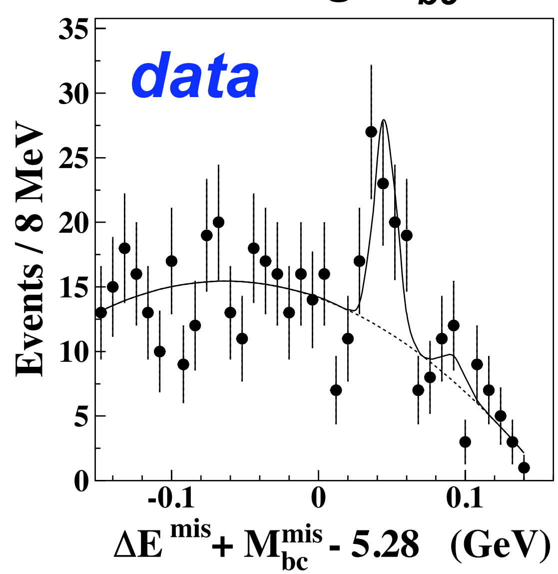


Results for $\mathcal{B}(\Upsilon(5S) \to BB)$:

BB:	*(5.5 ± 1.0 ± 0.4)%*
*B*B:*	*(13.7 ± 1.3 ± 1.1)%*
*B*B*:*	*(37.5 ± 2.1 ± 3.0)%*

Combine B with a π, calculate missing M_{bc}, ΔE:





Results for $\mathcal{B}(\Upsilon(5S) \to BB\pi)$:

BBπ:	*(0.0 ± 1.2 ± 0.3)%*
*B*Bπ:*	*(7.3 ± 2.3 ± 0.8)%*
*B*B*π:*	*(1.0 ± 1.4 ± 0.4)%*

Summary

- Belle has measured the absolute branching fractions of Cabibbo-favored $B_s \to D_s^{(*)}\pi/\rho^+$ decays; may become the main normalization mode at LHCb

- Belle has measured the branching fraction for $B_s \to D_s^{(*)} D_s^{(*)}$ and from this measurement determines the difference in decay widths $\Delta\Gamma_s/\Gamma_s$. Result is competitive with (and complementary to) CDF/D0

- Belle has measured $B_s \to J/\psi\, \eta$, $B_s \to J/\psi\, \eta'$ decays (CP eigenstates)

- Belle has measured the branching fraction for the charmless decay $B_s \to K^+K^-$

- Belle has measured the radiative decay $B_s \to \phi\gamma$ and searched for $B_s \to \gamma\gamma$

- Belle has studied $\Upsilon(5S)\to\Upsilon(nS)\pi^+\pi^-$ decays, finds a partial width >50 x larger than expected. The energy dependence does not match hadronic scan data.

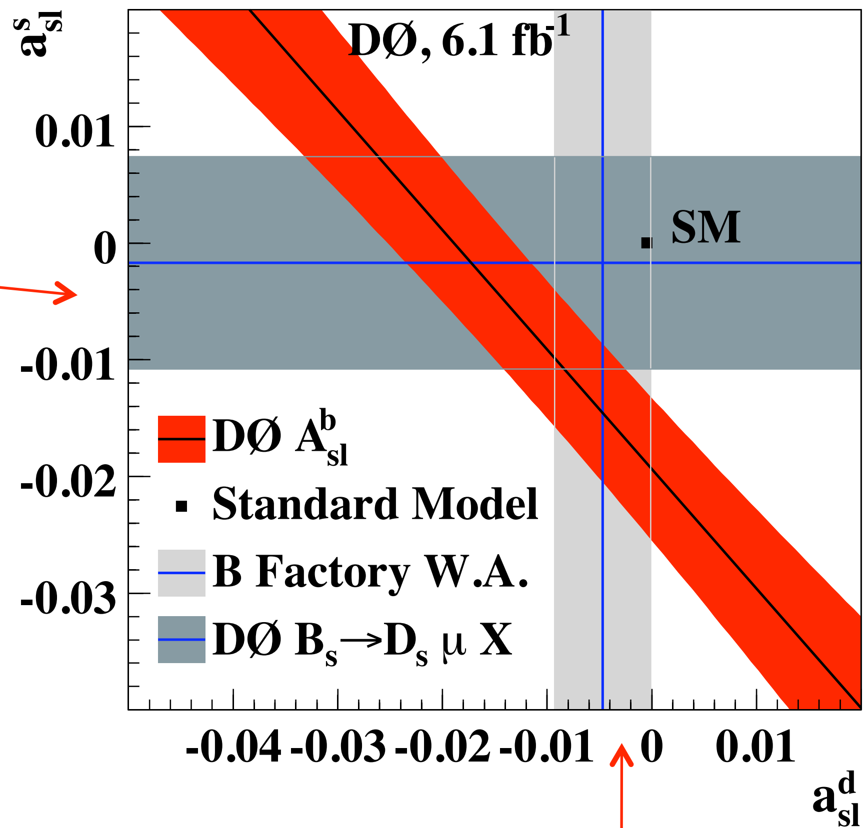
- Belle has measured the branching fractions for $\Upsilon(5S)\to BB(\pi)$, $B^*B(\pi)$, $B^*B^*(\pi)$

All these results are with 23.6 fb^{-1}. We now have 121 fb^{-1} (5.1x) recorded and being analyzed; we expect substantial improvements.

Future: Belle II should be able to record 40 x 121 = 5000 fb^{-1} of $\Upsilon(5S)$ data

dilepton asymmetry in B_d, B_s decays?

Can potentially be improved using Belle Υ(5S) dataset



Will be improved using full Belle Υ(4S) dataset